Improvement of the Cloud Physics Formulation in the U.S. Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)

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Grant Number: N00014-03-1-0304
http://www.cimms.ou.edu/

LONG-TERM GOALS

Correct representation of cloud processes is critical in producing accurate numerical weather prediction (NWP) forecasts. The major goal of the project is to develop state of the art parameterizations of cloud processes and implement them into COAMPS.

OBJECTIVES

Accurately representing cloud processes over a mesoscale model grid volume is currently hindered by inadequate representation of aerosol-cloud microstructure interactions. To resolve these present model shortcomings, we will develop a comprehensive formulation of cloud-aerosol interactions which will include parameterizations of aerosol activation processes and the effects of giant aerosols.

APPROACH

During previous years we have developed and implemented into COAMPS a new bulk microphysical parameterization. Our results have demonstrated that including drizzle processes has a strong influence on internal cloud characteristics and mesoscale cloud geometry (Mechem and Kogan 2003). Recently, using this bulk microphysical framework in COAMPS, we have explored aerosol-cloud-drizzle interactions for various aerosol distributions and source rates. These results were the first step in developing a formulation of aerosol source rates and accounting for remotely sensed aerosol parameters in a mesoscale model framework.

The first phase of our bulk microphysical parameterization incorporated into COAMPS included a single prognostic equation for total CCN concentration. Results from previous work by our group based on LES simulations (L. Yi, Y. Shprits) determined the microphysical parameters most critical in dictating cloud microstructure and the development of precipitation. These results argued for representing aerosol effects in bulk schemes using three parameters: the total concentration of CCN nuclei (N_t), the concentration of CCN in the range of 0.04-0.1 μm, roughly corresponding to large Aitken nuclei (N_a), and the concentration of giant CCN with radii greater than 1 μm (N_g).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Improvement of the Cloud Physics Formulation in the U.S. Navy Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Oklahoma,Cooperative Institute for Mesoscale Meteorological Studies,100 East Boyd, Room 1110,Norman,OK,73019**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Our previous treatment of aerosol activation in COAMPS was based on the empirical relations of Martin et al. (1994) and O'Dowd et al. (1996) that related bulk CCN and cloud droplet concentration. This method of activation rigidly constrains the relationship between CCN and droplet number and thus has no way of responding physically to model dynamics (for example, the strength of an updraft and resulting supersaturation field). For this reason, we are developing an activation parameterization to be integrated into COAMPS that is able to respond to model dynamics and diagnose from CCN properties the concentration of nucleated cloud droplets. This task involves additional exploration using large eddy simulation (LES) of aerosol activation process beyond that done using simple parcel models, as well as formulating a subgrid-scale (SGS) closure based on turbulent kinetic energy (TKE, predicted by COAMPS) for updraft velocity or supersaturation.

The second thrust of our work on the formulation of aerosol-cloud-drizzle interactions is aimed at the development of a new parameterization that accounts for the effects of giant CCN. This parameterization uses precise representations of the condensational growth of aerosol particles in the subcloud layer and is based on directly observable parameters of giant CCN, such as concentration and the exponent of the Junge distribution of the aerosol spectra. The parameterizations of the activation process and the effects of giant CCN constitute the basis of the formulation of aerosol effects on cloud microstructure.

Finally, in developing parameterizations of sub-grid variability of cloud parameters for use in COAMPS microphysical routines, we are employing both LES and millimeter-wave cloud radar (MMCR) data. Under this task, we have tested the fidelity of different analytic probability distribution functions (PDFs) and variance closures for representing PDFs found in nature (Kogan et al. 2005).

WORK COMPLETED

The following tasks are in progress:

1. Developing a parameterization of CCN activation for bulk microphysical models

2. Formulation of a parameterization of giant CCN

Work has been completed on the following tasks:

1. Investigation of aerosol-cloud-precipitation interactions in COAMPS using the CIMMS bulk drizzle parameterization

2. Characterizing variability of cloud properties from cloud radar for use in parameterizations of subgrid inhomogeneity of cloud microphysical quantities

RESULTS

1. Parameterization of CCN activation

In classical theory, activation of CCN occurs when nuclei in the subcloud layer are transported upward in buoyant updrafts. A number of droplets will likely be nucleated (activation of CCN), depending upon the chemical composition and size characteristics of the aerosol. The nucleated droplets will be at an unstable equilibrium at that particular supersaturation and will begin growing by condensation, lowering the ambient supersaturation and resulting in a decrease in S with height following the motion. As expected, droplet number generally tends to be a maximum in these nucleation regions of strong updraft and large supersaturation.

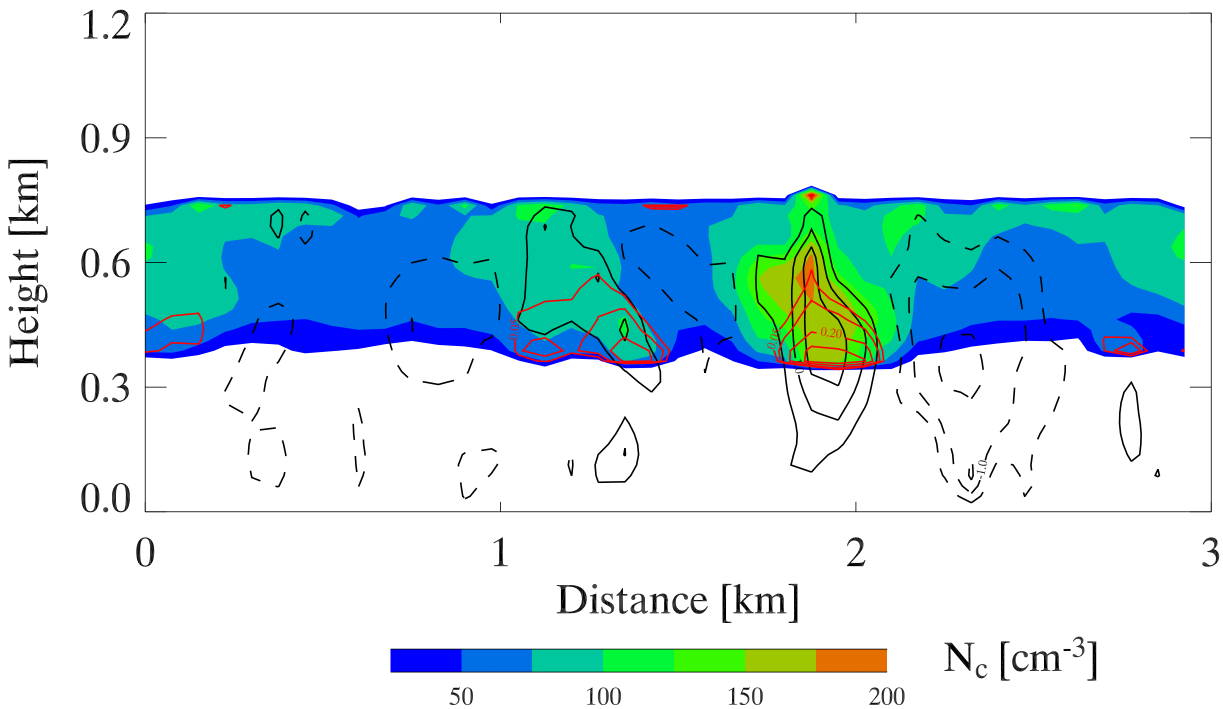

Figure 1. Vertical cross section from LES results illustrating activation of CCN. Color-filled contours are droplet concentration [cm^{-3}]. Black contours are updraft velocity, with negative values dashed (contour interval of 0.5 m s^{-1}). Positive values of supersaturation are denoted by red contours, with values of 0.05, 0.1, 0.2, and 0.3%.
[graph: Nucleation of cloud droplets occurs in regions of positive supersaturation associated with updrafts. However, the number of droplets is increasing with height, indicating that CCN activation continues from cloud base up to the level of maximum droplet concentration.]

Classical parcel theory predicts that all of the activation will occur at cloud base, where supersaturation is a maximum. Results from large eddy simulation (Figure 1), on the other hand, shows that for some updrafts (e.g. near X=1.9 km), the maximum in N_c is well above cloud base, indicating that additional droplet nucleation is occurring in a continuous fashion from cloud base up to the level of maximum N_c. This activation is nevertheless restricted to supersaturated regions, and evidence strongly suggests that CCN are being supplied to the supersaturated updraft via lateral entrainment. Parcel models neglect

this effect, and we are exploring to what extent the neglect of the additional CCN activation by parcel models leads to an underestimate of cloud N_c.

N_c at cloud base is well correlated with vertical velocity, especially over supersaturated regions at cloud base (Figure 2a), and the dependence can be represented as a simple power law. This relationship is reflected in frequently employed CS^k relations and the fact that vertical velocity is a primary factor in determining supersaturation. The relationship between nucleated droplet concentration and updraft is more complicated when the analysis is expanded to all supersaturated regions (the gray "+" marks in 2a), since the secondary activation occurring in some of the updrafts is captured. Rather than simply areas of supersaturated cloud base, we argue that all regions of positive supersaturation, including those inside the cloud, more completely represent the aerosol activation zone.

Probability distribution functions (PDFs) in Figure 2b indicate that mean droplet concentration is indeed higher when all supersaturated regions are considered, relative to N_c over supersaturated cloud base regions only (82 vs. 72 cm^{-3}), the difference likely being the direct result of the continuous activation process occurring in the rising parcel. Cloud mean values of N_c for this particular case are 69-71 cm^{-3}, depending on the sampling method employed. The cloud mean values are never greater than the droplet concentrations over the supersaturated nucleation regions.

A power law between activated CCN and vertical velocity, PDFs of vertical velocity, and a closure to relate mesoscale TKE to the vertical velocity PDFs form the basis for a parameterization of activation. The activation power law will vary, depending upon the characteristics of the ambient aerosol. LES results suggest a Gaussian or triangular distribution as a reasonable approximation for the vertical velocity PDF. Integrating the power law in Figure 2a over an assumed velocity PDF based on a TKE of 0.37 m^2 s^{-2} predicts a mean N_c of 68 cm^{-3}, which underestimates the LES mean cloud N_c by only ~5%. Work is ongoing to relate the activation power law to aerosol properties such as total concentration and shape of the spectrum.

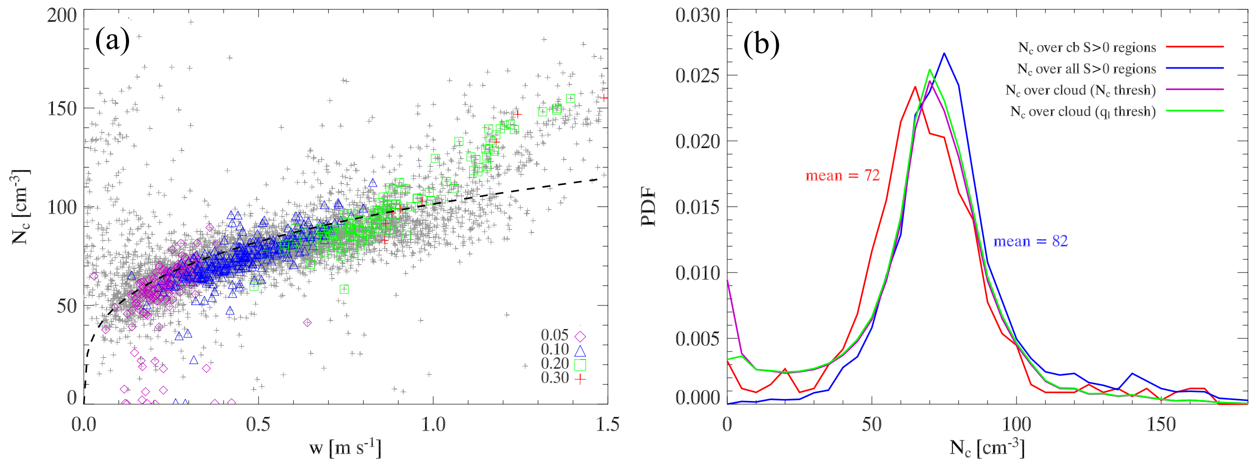

Figure 2. (a) Scatterplot of cloud base droplet concentration as a function of updraft magnitude, stratified according to supersaturation (%). Grey "+" marks represent all supersaturated regions. Dashed curve represents a power law fit of $109.4w^{0.459}$***. (b) PDFs of droplet concentration throughout the cloud (purple and green lines) and conditionally sampled over supersaturated cloud base (red line) and all supersaturated regions (blue line).***
[graph: (left) Droplet concentration increases as a function of w and may be approximated as a power law. (right) PDFs of droplet concentration are nearly Gaussian, with the PDF over cloud base supersaturation lying to the left of the PDF over all supersaturated regions. The cloud-mean PDFs lie in between.]

2. Parameterization of giant CCN

Our group's previous work has emphasized the importance on the precipitation process of representing giant CCN (aerosol particles with radius larger than 1.0 micron) in a bulk microphysical model. A parameterization of giant CCN, which can be straightforwardly implemented into current bulk microphysical schemes, has been formulated. The parameterization is based on first principles and parameters directly measured in observations, such as total concentration of giant aerosols and the exponent of a Junge power law aerosol distribution. These parameters combined with precise calculations of the CCN wetting due to condensational growth in the subcloud region allow for the calculation of a water substance source term incorporated into the bulk scheme rainwater equation. The activation problem is straightforward for the giant part of the aerosol spectrum, since nuclei larger than 1 μm are easily activated at small values of supersaturation.

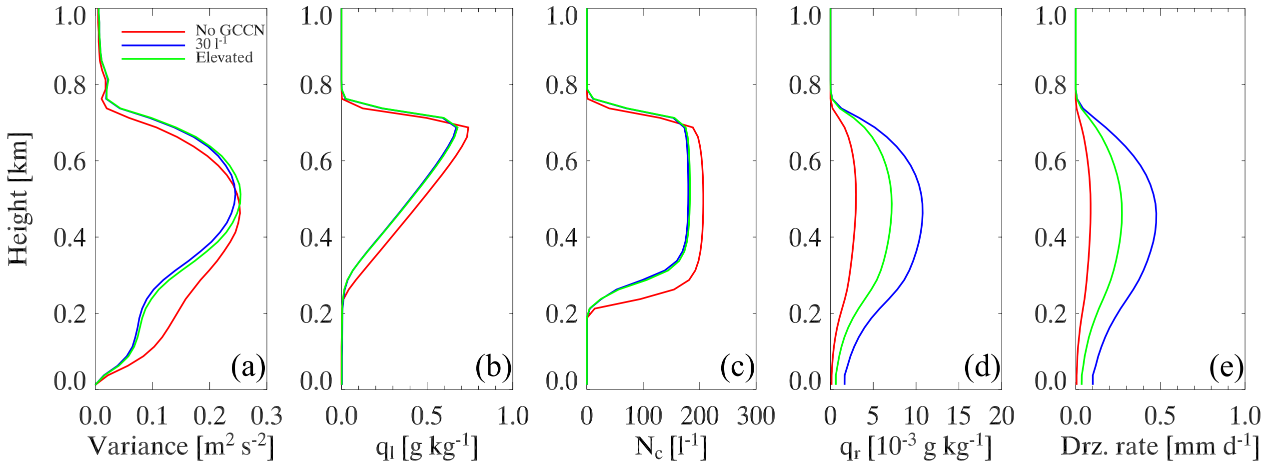

Figure 3. Vertical profiles of mean LES quantities for the control (red) and giant CCN (blue and green) simulations. See text for simulation descriptions. (a) Vertical velocity variance; (b) q_l; (c) N_c; (d) q_r; (e) Drizzle rate.
[graph: The effect of both giant CCN sensitivity experiments is to reduce PBL mixing, liquid water mixing ratio, and droplet concentration. The amount of drizzle water and drizzle rate increases.]

Figure 3 summarizes results from three simulations with different aerosol characteristics and spatial distributions. The aerosol properties in the control experiment are characterized as a background sulfate mode with a total concentration of 628 cm^{-3}, while the giant CCN experiments contain both the background sulfate mode plus a giant CCN contribution of 30 per liter. Giant CCN in the "elevated" experiment are present only above the inversion and constitute a source term representing entrainment of CCN from the free troposphere. These simulations of the giant CCN parameterization in a bulk microphysical framework are consistent with many previous simulations based on explicit spectral microphysical simulations. For example, the simulations show an increase of drizzle rate when giant CCN are added to a background aerosol field. Both giant CCN simulations enhance drizzle throughout the boundary later, increase the depletion of liquid water and droplet concentration, and begin to modulate the boundary layer dynamics toward a decoupling of cloud- and subcloud-layer circulations.

Other simulations demonstrate that the impact of giant CCN on cloud structure and dynamics depends strongly on the amount of pollution in the environment and on the amount of moisture in the boundary layer. The most dramatic increase in drizzle production is shown in Figure 3 and results when giant CCN are added to a nonprecipitating cloud with a high background aerosol concentration. A simulation in which giant CCN is added to a low background sulfate concentration (82 cm^{-3}) only modestly enhances drizzle production. In addition to the ambient aerosol characteristics, the amount of boundary layer moisture strongly influences drizzle production and the effect of drizzle on boundary layer dynamics. A moister boundary layer means a thicker cloud layer (for a given layer temperature θ_l), greater liquid water content, and stronger drizzle production. On the other hand, falling drizzle will more readily evaporate when falling through a dry subcloud layer, and the resulting thermodynamic stratification can change the character of the boundary layer turbulence, leading to a decoupling of the boundary layer into cloud- and sub-cloud circulations. These simulations produce stronger drizzle when giant CCN are added to the moist case, while the dry case exhibits a more significant change in the turbulent statistics (dynamics). These sensitivities to background CCN and

moisture, utilizing a bulk microphysical parameterization, are in agreement with our past work employing size-resolved microphysical processes. These results illustrate the importance of accounting for giant CCN in mesoscale model framework and the ability of the parameterization to respond in a physically meaningful manner to a wide range of environmental conditions.

3. Characterizing SGS variability of cloud properties from MMCR

Neglecting subgrid-scale (SGS) variability in numerical models can lead to substantial biases in radiative quantities and microphysical process rates, both of which can be highly linear. These biases arise when microphysical or thermodynamic quantities are simply calculated from predicted grid point variables, an operation that assumes the quantity is homogeneous over the grid volume. Unbiased quantities can be calculated, provided the distribution function of relevant quantities is known. These distributions are typically specified as probability distribution functions (PDFs), with lower order moments describing the PDF either predicted or determined from observational or model data. We have been using PDFs obtained from MMCR data to test the fidelity of PDF types commonly employed for representing SGS variability in numerical models.

We tested the performance of various analytic distributions in calculating unbiased precipitation flux from MMCR data (Kogan et al. 2005). Figure 4 shows the error associated with assuming zero variability, i.e. the subgrid variability bias. Relative error from subgrid variability bias is always negative and begins near zero for small variances and increases in magnitude to as large as 0.7. The unbiased precipitation rate calculated using these analytic distributions was compared to the rate integrated over the complete observational PDF. We tested both Gaussian and Gamma distributions, with several different methods of constraining free parameters, for boundary layer (BL) clouds and a more general low altitude (LA) cloud category. The observational mean reflectivity was taken to be the mean of the analytic distribution, but various methods for approximating the variance were attempted. We tested cases of a constant variance, a scale dependent variance closure defined as a function of mean reflectivity, and a variance obtained from the observational PDF. The Gaussian distribution, with mean and variance taken from the observational PDF (simulation 2P), performed the best, accounting for 75% of the subgrid variability bias for both boundary layer clouds and a more general low cloud category (Figure 4a and b). Performance of the fixed variance method (simulation FS) was poor, and in fact overestimated subgrid heterogeneity for cases where the observed PDF variance was smaller than the assumed fixed value. The variance closure based on the mean value (not shown) was an improvement over using a fixed variance but less accurate than knowing the actual PDF variance. In this particular application, the Gaussian distribution performed better than the Gamma (simulation GM). The results of Kogan et al. (2005) indicate that assumed Gaussian PDFs are a good choice for evaluating unbiased grid-mean microphysical process rates but would greatly benefit from an improved variance closure.

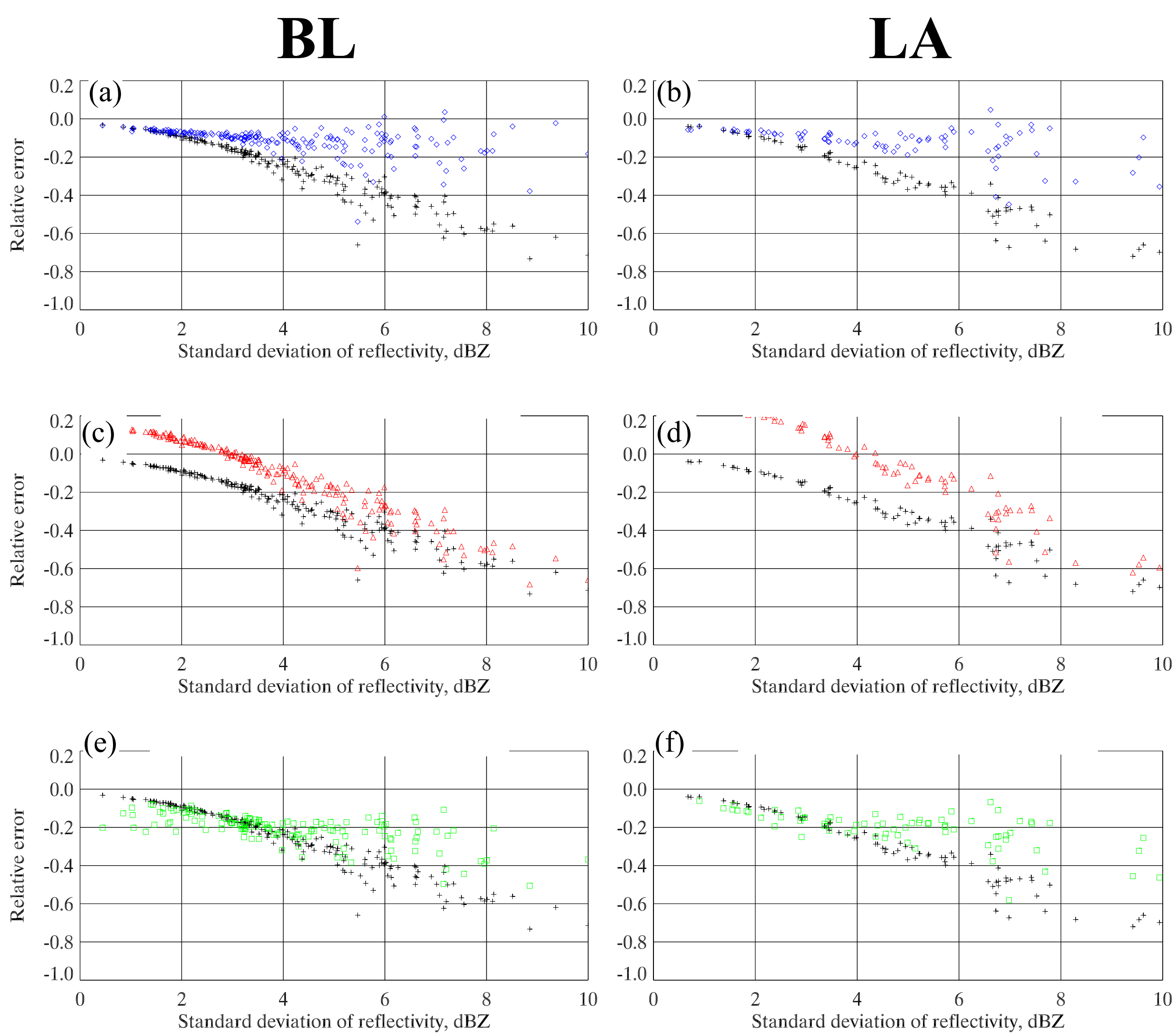

Figure 4. Relative error in grid volume mean precipitation flux, assuming analytic approximations to the full PDF for BL and LA clouds. Black crosses in (a)-(f) represent the subgrid variability bias. (a)-(b) 2P. (c)-(d) FS. (e)-(f) GM. See text for descriptions of 2P, FS, and GM simulations. [graph: Subgrid variability bias is always negative and begins near zero for small variances and increases in magnitude to as large as 0.7. The error magnitude for a Gaussian distribution with known mean and variance is between 0.1 and 0.2 for both cloud types. Error for a fixed variance is positive for small values of variance and negative for larger values. The magnitude of error for the Gamma distribution lies in the range of 0.2 to 0.5.]

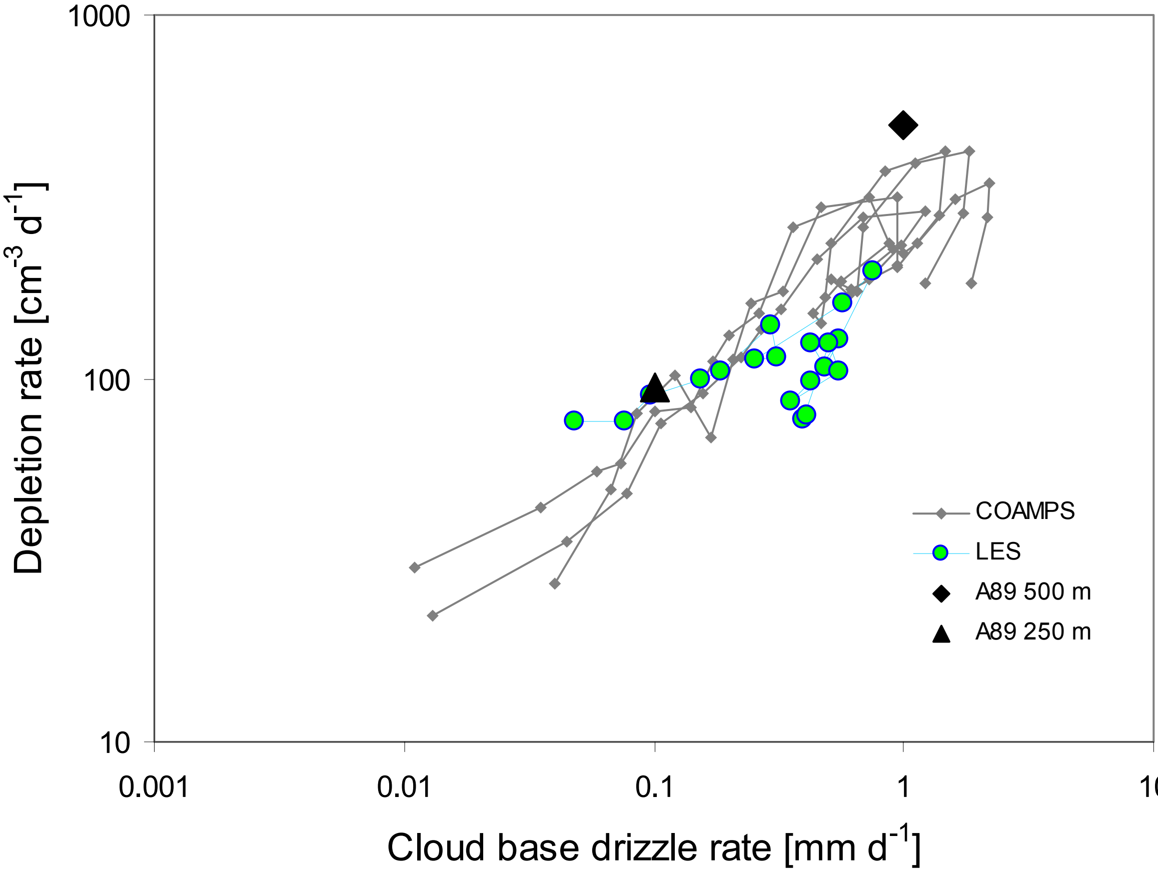

Figure 5. CCN depletion rate as a function of cloud base drizzle rate for four COAMPS simulations (grey lines, each representing different initial CCN concentrations) and LES (turquoise circles). The diamond and triangle represent theoretical calculations as in Albrecht (1989) for clouds of thickness 500 m and 250 m, respectively.
[graph: COAMPS depletion rate and cloud base drizzle rate are correlated on a log-log (power law) scale. Calculations by the method of Albrecht lie near the realm of COAMPS and LES results.]

4. Aerosol-cloud-precipitation interactions in COAMPS

We have built on our previous efforts on representing cloud processing of aerosol using bulk microphysical models. Regional model aerosol depletion rates were calculated from the Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) equipped with the CIMMS bulk drizzle scheme. In an attempt to constrain cloud processing rates calculated from regional model simulations, large eddy simulations (LES) of matching cases were analyzed. The LES model explicitly represents the turbulent dynamics and bin-resolving microphysical processes, which are for the most part parameterized in the regional model. Depletion is calculated in COAMPS from a budget residual of total particle concentration, while in the LES is based on the coagulation process. For the purpose of this comparison the two methodologies may be considered equivalent. COAMPS depletion rates in Figure 5 compare favorably with the LES, though the range of the LES rates is smaller. As aerosol are consumed by cloud processing, the depletion rate in the LES peaks somewhat earlier and at a smaller magnitude than in COAMPS, implying that cloud processing may be somewhat self-regulating when a more complete treatment of dynamical and

microphysical processes is included. Both COAMPS and LES depletion rates are in the range of theoretical calculations of cloud processing using the simple calculations along the lines of Albrecht (1989).

IMPACT/APPLICATIONS

Improved parameterization of cloud physical processes will result in more accurate numerical weather prediction for U.S. Navy operations. Current results are relevant to more accurate forecasts of cloud persistence and radiative parameters.

TRANSITIONS

Future improvements to the COAMPS cloud physics parameterization package (activation parameterization, giant CCN parameterization, SGS variability) developed at CIMMS/OU will be made available to NRL and registered COAMPS users at large.

RELATED PROJECTS

We are leveraging our involvement in the Department of Energy Atmospheric Radiation Measurement Program (DoE ARM) for this project. Our ARM research involves using millimeter-wave cloud radar to measure spatial and temporal variability of cloud fields in order to derive PDFs for various cloud types. Results directly relevant to this project are summarized in Results Section 3.

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